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MODELING THE 17 JANUARY 1997 DELTA-II EXPLOSION BY ARAC, ADORA, AND REEDM

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1. INTRODUCTION

A Delta-II rocket exploded during launch from Launch Complex 17 at Cape Canaveral on 17 January 1997. Following reports of the explosion, the Atmospheric Release Advisory Capability (ARAC) modeled the resulting cloud of toxic gas. ARAC modeled the release as a cloud of neutral gas, and the results successfully simulated several aspects of the reported behavior of the actual cloud.

However the ARAC dispersion model does not describe the transforming behavior of reactive chemicals, so it was unable to predict completely the evolution of the cloud. ARAC suggested to BlazeTech Corporation, which created the ADORA (Atmospheric Dispersion Of Reacting Agents) system, that a collaboration would be interesting, as ADORA is capable of predicting the chemical and thermodynamic transformations and the buoyant rise of the cloud. Therefore, ADORA was used to model the Delta-II explosion, and the resulting puff characteristics, including the major chemical species and their amounts, and the size and the stabilized height of the cloud, were used as a source term in the ARAC dispersion modeling system.

The Rocket Exhaust Effluent Diffusion Model (REEDM) system is used operationally at Cape Canaveral to model the behavior of rocket exhaust clouds and to evaluate the potential threat to health from the toxic gases present in those clouds. The REEDM system, supported by ACTA, Inc., simulates cloud rise to stabilization, followed by movement by a transport mechanism. ARAC contacted ACTA for information about the Delta-II explosion, and discussions led to including REEDM in this study. Thus, the REEDM cloud stabilization prediction for the Delta-II explosion was used as input to the ARAC models, to demonstrate an alternative dispersion calculation.

In this paper, we present the results of the following five model calculations:

- ARAC
- ADORA and ARAC
- REEDM
- REEDM and ARAC with ARAC winds
- REEDM and ARAC with rawinsonde winds.

We then compare each result with observations of the cloud's behavior.

2. RELEASE DESCRIPTION, PLUME BEHAVIOR, AND AMBIENT CONDITIONS

The Delta-II launch began at 1628 UTC on 17 January 1997. After 12.5 sec, when the rocket had reached a height of 484 m, it exploded. This initial explosion destroyed only the first stage and the boosters. (The Delta-II is a three-stage liquid-propellant vehicle with nine solid-propellant strap-on booster motors.) Burning rocket fuel formed a buoyant toxic cloud. The second and third stages and payload survived the initial explosion and drifted upward to about 760 m at 22.4 seconds. Destruct signals were sent at this point, and the exploding second-stage hypergolic fuel formed a second toxic cloud which rose due to buoyancy.

The clouds drifted in two primary directions. The lower cloud drifted southward over the Atlantic Ocean south of Cape Canaveral, and the upper cloud moved toward the east over the ocean. The cause of the difference in direction was strong wind shear across a temperature inversion at about 910 m. Winds below the inversion were brisk (11 m sec^{-1}) and from the

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north or north-northwest. Immediately above and below the base of the inversion the observed winds were within a few degrees of due northerly, then backed rapidly with height, becoming northwesterly above 1350 m and westerly above about 2400 m.

The cloud motions were tracked by the National Weather Service WSR-88D Doppler radar in Melbourne, Florida. The radar is located approximately 37 km south of Cape Canaveral. Every 10 minutes, the radar scanned a horizontal radial of 360 degrees at five vertical elevation angles ranging from 0.5 to 4.5 degrees (Fig 1).

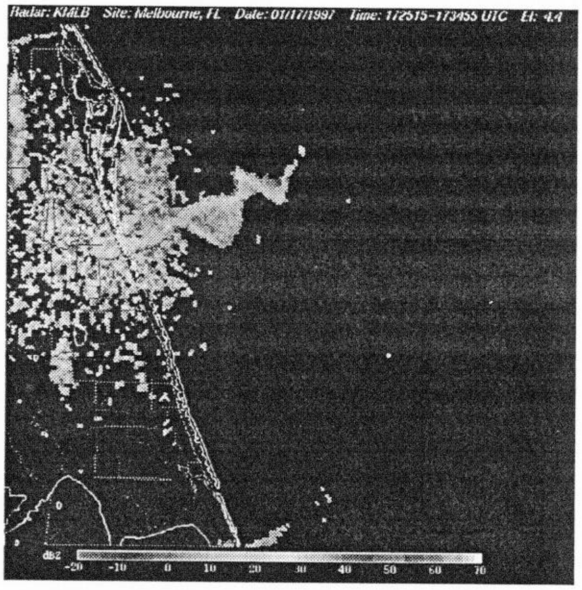

Figure 1. Composite image from Melbourne NWS radar, scanned from 1725-1734 UTC, 17 Jan 97.

Radar reflectivity measurements of the resulting cloud provide the best available estimates of the location and dimensions of the cloud over a four-hour period after the explosion. The radar's beam width and volumetric averaging prevent precise measurements of the cloud dimensions. However, preliminary analysis of the scan ending at 1636 UTC indicates the low level cloud was approximately 3 km long, 2 km wide, and at least 2 km thick and was located 1 km from Launch Complex 17. The bottom of the could not be determined because the explosion occurred during one of the radar's scans. The upper level cloud was approximately 4 km long, 4 km wide, and 1.5 km thick and was located 6 km east of Launch Complex 17. The top of this cloud was approximately 3200 m above the surface.

A local television station's Doppler weather radar also tracked the lower cloud. Both radars showed the lower cloud moving over land between Cocoa Beach and Melbourne, but neither could determine whether that part of the cloud reached the surface. Local observers reported the cloud was aloft but not at the surface, but there were no concentration measurements to reveal whether or where the cloud at the surface reached land.

3. ARAC DESCRIPTION

ARAC operates a suite of models which are used to evaluate the consequences of releases of hazardous materials in the air (Sullivan et al., 1993). The ARAC system generates a time-varying series of three-dimensional mass adjusted wind fields, which are used to drive the ADPIC Lagrangian particle dispersion model. As input to its wind field calculations, ARAC can use a variety of data sources, including observational data and gridded data output from numerical weather prediction models. ARAC supports a wide range of actual or potential releases of hazardous materials in the atmosphere, including NASA missions involving nuclear material, such as the Mars Pathfinder and Cassini missions (Pace, 1998). The Delta-II mission involved no nuclear material, but ARAC decided to model the explosion as an internal evaluation of its ability to respond to an accident at the Cape.

For its support to Cassini, ARAC developed procedures to use meteorological data from the rich observational network at the Cape, including wind profilers and over 40 instrumented multi-level towers, as well as gridded output from ARAC's execution of the Navy Operational Regional Atmospheric Prediction System (NORAPS). ARAC used the same data sources to study the Delta-II explosion.

4. ARAC INITIAL MODELING RESULTS

ARAC used a 16 hr forecast from a NORAPS run initialized at 00 UTC on 17 Jan 97, plus local observations, to create a detailed three-dimensional wind flow pattern which clearly depicted the strong wind shear due to the presence of the inversion. The winds moved the cloud quickly away from the Cape, so only a single 3-D representation was used. For longer events, ARAC would have developed a series of 3-D grids to show the time evolution of the situation.

The calculated wind field showed northerly or northwesterly flow at the lowest levels. Over land and just offshore, the winds shifted to north-northeasterly at levels between 900 and 1350 m AGL, while farther offshore the winds at these levels remained northerly. (Note that the northeasterly component developed by NORAPS was not seen in the observations used in this run.

However northeasterly winds at some level south of the Cape are consistent with the cloud behavior. Also a sounding taken at the Cape at 1613 UTC, just before the launch, showed a slight north-northeasterly wind component between 600 and 900 m AGL.) At higher levels, the winds backed rapidly all across the domain, becoming northwesterly above 1800 m and westerly above 2000 m.

The ARAC system contains a time-dependent explosive cloud rise algorithm, but this capability currently simulates only the particulate products from explosions. Further, the ARAC system cannot treat reactive chemical processes. Therefore, for its initial calculations, ARAC simply inserted a sphere containing an arbitrary mass of neutrally buoyant non-reactive gas at the height of the explosion (484 m). Since all the material in this simulation remained below the inversion, the entire puff moved southward (Figs 2 and 3), with the cloud aloft spreading over land north of Melbourne.

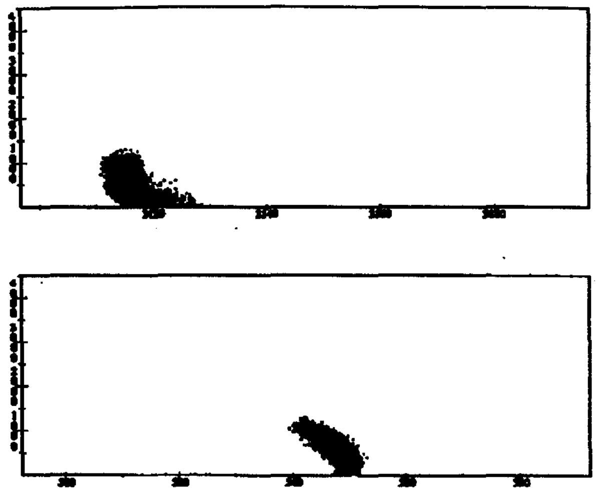

Figure 3. Vertical cross-sections of ARAC cloud based on arbitrary source term, 1 hr after release. (Top) View from east toward west. (Bottom) View from south toward north. Vertical scale is m AGL.

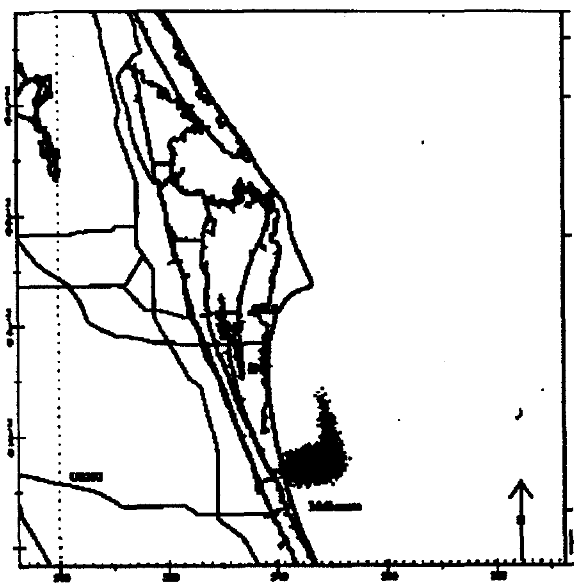

Figure 2. Top-down view of ARAC particle positions based on arbitrary source term, 1 hr after release. Abscissa and ordinate scales are Universal Transverse Mercator (UTM) distances, equivalent to km.

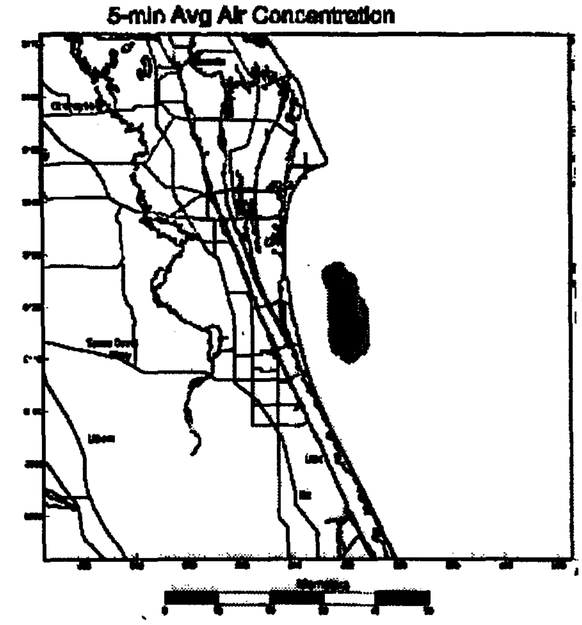

Figure 4. Maximum concentration of HCl at 1.5 m AGL based on arbitrary ARAC source term, 1 hr after release. Contour values not meaningful.

Because the source term was not accurately specified, the ARAC surface-level concentration magnitude predictions are not meaningful. However the position of the surface concentration maximum (Fig 4) is in general agreement with observations of the lower cloud.

ARAC had thus used local and forecast wind data to disperse a pre-defined fixed source, which was ARAC's approach for Mars Pathfinder and Cassini. Results were consistent with observed behavior (the eastward motion of the upper cloud was not represented, but at that time ARAC was not aware of the existence of the upper cloud), so ARAC considered this internal exercise to be successfully completed (Albritton et al., 1997). The opportunity to combine ADORA with ARAC re-opened ARAC's interest in the Delta-II event. This led to contacts with personnel at the Cape who provided more complete information about the actual cloud, and with the scientists who operate REEDM.

5. ADORA DESCRIPTION

ADORA is an advanced atmospheric dispersion model for reacting chemicals, developed based on proven engineering principles and modeling methodologies (Zhang et al., 1996 and Zhang et al., 1997). ADORA includes the complex interaction of plume and cloud physics, chemical reactions, and thermodynamic transformations, and also provides dispersion calculations. It has the following major features:

- source specification and near-source effects
- reacting and non-reacting releases
- thermodynamic behaviors including solid, liquid, and vapor phases and their changes
- accounting for fireball and ground-attached tail partitioning
- dispersion of heavy, neutral, or buoyant materials
- automated identification of the worst-case scenario.

The output from ADORA is a representation of the stabilized cloud following dissipation of the immediate heat and buoyancy effects, incorporating the complex chemical reactions that occurred in the explosion. ADORA also predicts the initial downwind dispersion of the cloud as it evolves and stabilizes. The ADORA stabilized cloud output data are readily input to the ARAC system, which has a sophisticated transport and diffusion model. Pairing ADORA's explosive and reactive cloud representation and ARAC's dispersion modeling combines the strengths of the two systems, and the Delta-II event provided an ideal opportunity to evaluate this combination.

6. ADORA MODELING RESULTS

The ADORA simulation of the explosion was based on a post-accident analysis (Overbeck, personal communication) which estimated the contribution to the toxic cloud came from all the propellants released before the explosion plus the solid propellants from stage 0 which remained after the initial normal launch. This amount was input to ADORA. The effects of other propellants in the low-level explosion were neglected because most of them did not burn, some burned on the ground and so their contribution to the main cloud was small, and their quantification involves too much uncertainty. The ADORA output lists the mass of 17 different chemical species in the two segments, but for this study ARAC modeled only HCl, as that material is often the launch hazard of primary interest.

The ADORA output used by ARAC consisted of two segments: a sphere of diameter 915 m centered at 2155 m AGL, and a tail that extended from the upper cloud down to the surface. ADORA predicted a total of 7230 kg of HCl, with 3630 kg in the upper cloud and 3600 kg in the tail. ADORA calculated the cloud would move 2417 m downwind in 3.6 min following the explosion. At this point the cloud transitioned to passive (neutrally buoyant, non-reactive) dispersion, and was used as the ARAC source term.

7. COUPLED ADORA-ARAC MODELING RESULTS

The output from the combined ADORA-ARAC system (Figs 5 and 6) matches radar observations of the cloud's behavior very closely. The part of the tail below the inversion moved southward over the ocean. The lowest part of the tail, at the surface of the water, remained offshore for almost 90 min, finally coming onshore south of Melbourne. The cloud aloft (between 500 m and 1500 m AGL) moved over the land much farther north, just south of Cocoa Beach. The upper level cloud extended far eastward over the ocean.

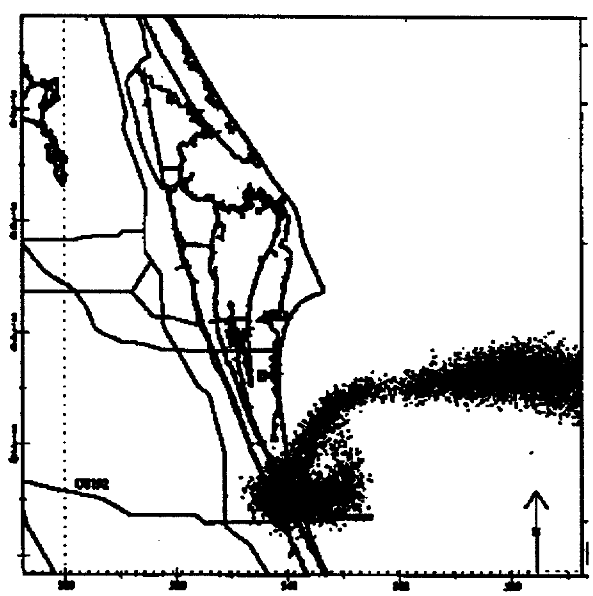

Figure 5. Top-down view of ARAC particle positions based on ADORA source term, 1 hr after release.

In this simulation, all the material remained below 2800 m AGL, extending upward into the northwesterly and westerly winds. Peak HCl concentrations at the surface were between .001 and .01 ppm during the first hour following the accident (Fig 7).

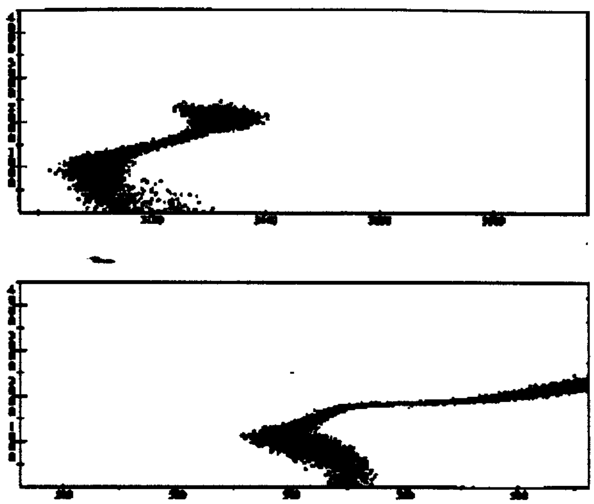

Figure 6. Vertical cross-sections of ARAC cloud based on ADORA source term, 1 hr after release. (Top) View from east toward west. (Bottom) View from south toward north.

8. REEDM REAL-TIME CALCULATION

Pre-launch REEDM predictions are used operationally at Cape Canaveral to assess the potential toxic chemical hazard to on-base personnel and the off-base public. If exposure limits are predicted to be exceeded, the launch will be held.

The REEDM computer program models the behavior of rocket exhaust clouds. During normal launches, the burning of rocket fuel during the first few seconds after ignition results in the formation of a large cloud of hot, buoyant exhaust products near the ground. The cloud lifts off the ground, grows rapidly through entrainment of ambient air, and rises to its stabilization height. A similar but larger cloud forms in the event of a catastrophic launch abort near the ground.

The REEDM system calculates several processes as separate steps: cloud formation, cloud rise, cloud stabilization (at neutral buoyancy after heat exchange with the atmosphere) and cloud transport. The REEDM chemical source strength calculation predicts:

- peak concentration
- time-mean concentration
- dosage
- surface deposition of cloud constituents downwind from normal launches and launch failures.

A single rawinsonde sounding provides the input meteorological data for REEDM, which incorporates vertical but not horizontal wind shear. Thus the sounding is assumed to define the flow all across the model domain.

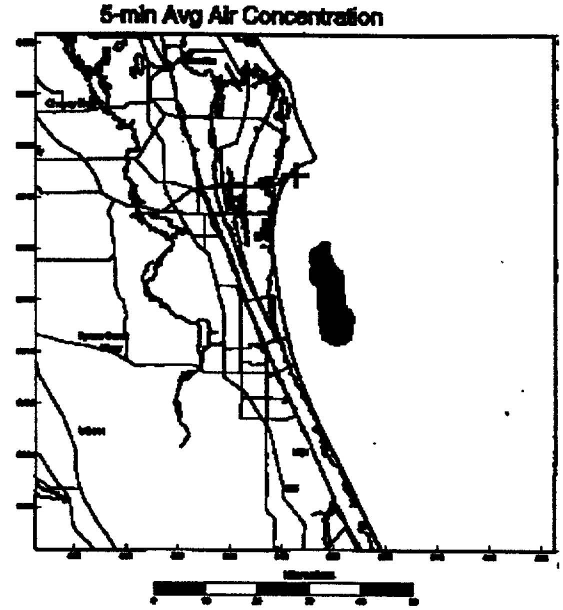

Figure 7. Concentration of HCl at 1.5 m AGL based on ADORA source term, 1 hr after release. Shaded area > .001 ppm.

Following the Delta accident, REEDM modeled only the lower toxic cloud, which was a potential health threat at the surface. The sounding detected northerly or northwesterly winds below the inversion, so the REEDM calculation drove the cloud southward, with landfall south of Melbourne. The peak HCl concentration predicted by REEDM as the plume moved southward was on the order of 1.0 ppm for the first 30 min; the highest peak (1.27 ppm) was predicted to occur 1.5 km downwind from the pad.

9. REEDM SOURCE TERM CALCULATION

The REEDM stabilized cloud for the lower level and upper level explosions is represented as a series of elements extending from the surface upward to about 1700 m. REEDM predicted each element's mass, size, and position. The total mass of HCl in the elements was approximately 15000 kg. In comparison with the ADORA source term, the REEDM source term does not extend as high, and has much more mass. The REEDM and ADORA source terms were based on different assumptions about how much material was involved in generating the toxic cloud.

10. COUPLED ARAC-REEDM MODELING RESULTS

The REEDM stabilized cloud elements were input to the ARAC 3-D dispersion model. Initially the ARAC-derived 3-D wind field combining NORAPS data and observations was used. In this run (Figs 8 and 9), the lower cloud moved toward the south, with the material at the surface moving south-southeastward and the material aloft moving toward the south-southwest, due to the northeasterly component in the NORAPS output.

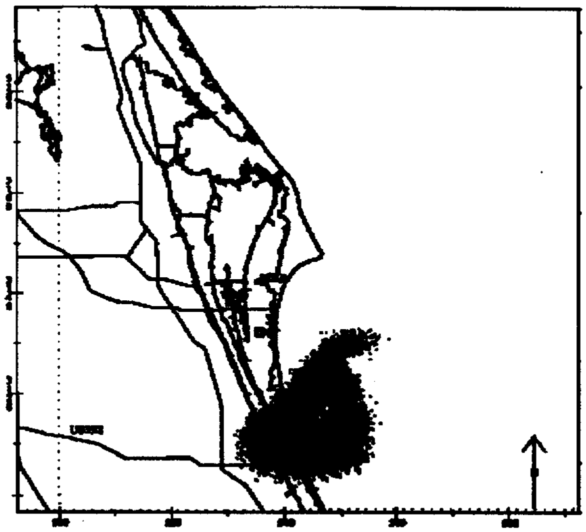

Figure 8. Top-down view of ARAC particle positions based on first REEDM source term, 1 hr after release.

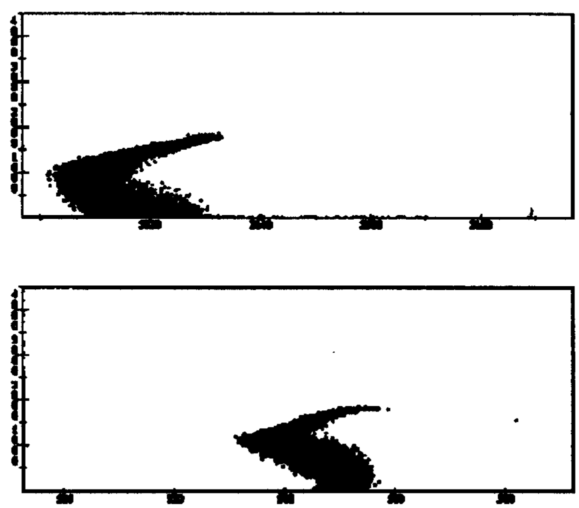

Figure 9. Vertical cross-sections of ARAC cloud based on first REEDM source term, 1 hr after release. (Top) View from east toward west. (Bottom) View from south toward north.

The material at the surface stayed offshore (as in the original REEDM calculation), and the part of the plume that moved over land was at an elevation of a few hundred meters. The upper level cloud, at about 1700 m AGL, showed a small extension to the northeast, but not the pronounced extension shown in the radar images, as strong westerly winds were not present at the elevation of the cloud in this wind field.

HCl concentrations close to the pad in this REEDM-ARAC simulation were similar to those in the original REEDM run, with peak values larger than 1 ppm. However, over the first 30 min, peak concentrations were lower--between .1 and .01 ppm--with peak values between .01 and .001 after the first hour (Fig 10).

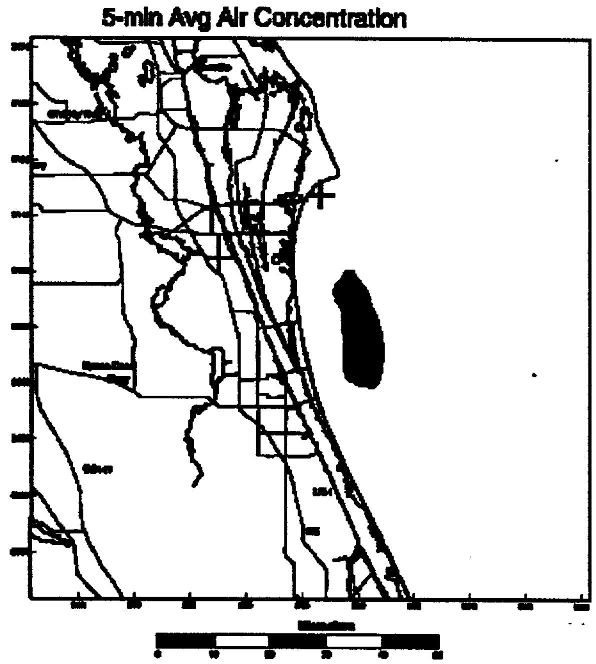

Figure 10. Concentration of HCl at 1.5 m AGL based on first REEDM source term, 1 hr after release. Shaded area > .001 ppm.

In a second REEDM-ARAC run, the NORAPS data and observations were replaced with the sounding taken at the Cape at 1613Z, 15 min before the explosion. In this run (Figs 11 and 12), a pronounced eastward extension of the upper cloud was seen, in good agreement with the radar images. The change is due to westerly winds at lower levels in the sounding than in the original ARAC wind field. The lower cloud position was farther west than in the first REEDM-ARAC run, and the surface plume moved onshore by 1711Z, just north of Melbourne. HCl concentrations (Fig 13) were about 50% larger than in the first run.

11. COMPARISON OF RESULTS

In several aspects the output from the two coupled runs using ARAC-derived winds was in close agreement, particularly with respect to the prediction near the surface and in the lowest

1500 m. The lower clouds moved in the same general direction, and the material aloft moved over land in the location indicated by the radar images. The second REEDM-ARAC cloud moved in a somewhat different direction than the other runs, with the HCl maximum at the surface moving onshore much farther north.

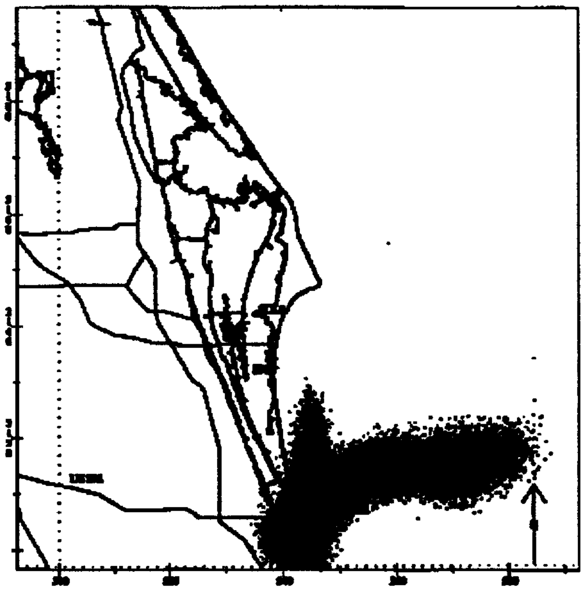

Figure 11. Top-down view of ARAC particle positions based on second REEDM source term, 1 hr after release.

There were two key differences in the runs. The REEDM and both REEDM-ARAC peak concentrations were higher (at least initially) than the ADORA-ARAC values, which is consistent with the much larger mass of HCl in the REEDM source term. Also the eastward extension of the upper level plume was seen clearly in ADORA-ARAC and in the second REEDM-ARAC run but not in the first REEDM-ARAC run. Generating this more realistic depiction of the upper cloud required the cloud to extend vertically into strong westerly winds which were seen at lower levels in the rawinsonde data.

12. SUMMARY

This collaboration illustrates the strengths and weaknesses of the three modeling groups. A combination of the source modeling in REEDM or ADORA with a 3-D dispersion model such as ARAC could produce an improved operational launch support capability.

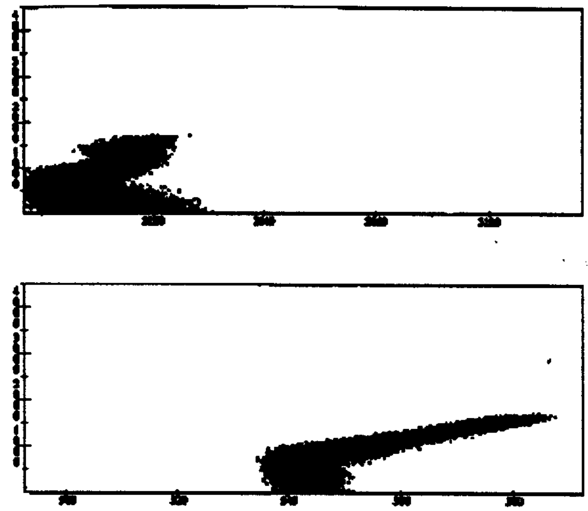

Figure 12. Vertical cross-sections of ARAC cloud based on second REEDM source term, 1 hr after release. (Top) View from east toward west. (Bottom) View from south toward north.

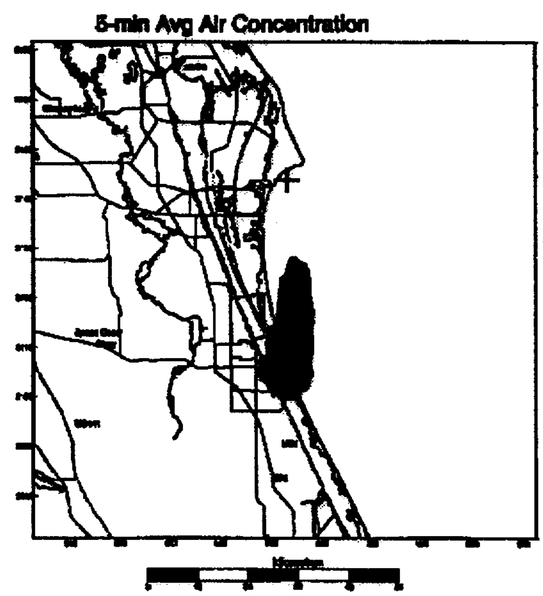

Figure 13. Concentration of HCl at 1.5 m AGL based on second REEDM source term, 1 hr after release. Shaded areas > .01 ppm and .001 ppm.

13. ACKNOWLEDGMENT

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